

Teleoperator Comfort and Psychometric Stability: Criteria for Limiting Master-Controller Forces of Operation and Feedback During Telemanipulation

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Abstract

In this paper we address the following question: How much force should we require operators to exert, or experience, when operating a telemanipulator master-controller for sustained periods without encountering significant fatigue and discomfort, and without loss of stability in psychometric perception of force. The need to minimize exertion demands to avoid fatigue is diametrically opposed by the need to present a wide a range of force stimuli to enhance perception of applied or reflected forces. For 104 minutes subjects repetitiously performed a series of 15 s isometric pinch grasps; controlled at 5, 15, and 25 percent of their maximum voluntary strength. Cyclic pinch grasps were separated by rest intervals of 7.5 and 15 s. Upon completion of every 10 minute period, subjects interrupted grasping activities to gage the intensity of fatigue and discomfort in the hand and forearm using a cross-modal matching technique. A series of psychometric tests were then conducted to determine accuracy and stability in the subject's perception of force experienced. Results showed that onset of sensations of discomfort and fatigue were dependent upon the magnitude of grasp force, work:rest ratio, and progression of task. Declines in force magnitude estimation slopes, indicating a reduction in force perception sensitivity, occurred with increased grasp force when work:rest ratios were greater than 1.0. Specific recommendations for avoiding discomfort and shifts in force perception, by limiting pinch grasp force required for master-controller operation and range of force reflection or work:rest ratios, are provided.

1. Introduction

Numerous questions have arisen in the course of design and construction of telemanipulator master-controllers and end-effectors; particularly, concerning the nature and magnitude of manipulative stimuli which should be presented to the controlling hand. Recent studies have

found that limiting muscle exertions to less than 20 percent of maximum voluntary contraction (MVC) levels is not an adequate design guideline for avoidance of localized muscle fatigue and discomfort for all muscle groups [1]. Moreover, population estimates of manual strength capability are very limited. These problems, when combined with insidious development of over-estimations of forces encountered during states of localized muscle fatigue [2], argue for minimization of forces experienced in either controller operation or reflected by the end-effector. However, diametrically opposing such a strategy is the fact that, depending upon the level of force required to simply operate the master-controller, severely restricting the dynamic range of force reflection could result in only very limited, and potentially useless, force information.

This design paradox led us to conduct a study to address the following questions. First, what are acceptable levels of force of operation, or force reflection, in terms of operator tolerance and stability of force perception? Second, do changes in force perception occur and, if so, do they precede alerting signs of discomfort and fatigue? Finally, if changes in force perception are found, are they due to an insidious loss of contractility in response to localized muscle fatigue, perceptual masking of proprioceptive stimuli produced by fatigue and discomfort symptomatology, or both?

2. Methods and Materials

Subjects. Four male (25.0 ± 7.3 years; maximum pinch force 131.5 ± 13.2 N) and two female (34.5 ± 3.5 years; maximum pinch force 103.0 ± 24.0 N) served as subjects. All subjects reported and appeared to be in good health with no history of musculoskeletal disease. Participation in the experiment was on an informed consent and paid basis.

Apparatus and Methods. Onset and severity of fatigue and discomfort in the hand and forearm, loss of pinch grasp force capability due to fatigue, and shifts in force perception were examined throughout a 104 minute period of cyclic grasping. Subjects performed pulp-pinch grasps with the thumb and index finger of the dominant-hand; the remainder of the digits formed a power-grip. Grasps were initiated and held for 15 s, and were followed by either a 7.5 or 15 s rest period. Subjects rested by maintaining the same hand posture in a relaxed state. Cyclic exertions were continued for 10 minutes. Upon completion of the ten-minute period, subjects performed a cross-modal matching procedure to estimate the severity of fatigue and discomfort in the working hand and forearm. Following this estimate, subjects then performed a force magnitude estimation task which was followed by rest for the remainder of the 3 minute period. The cycle of repetitious exertions followed by a 3 minute interval for measuring discomfort, measuring force perception capability, and then rest, was repeated for 8 consecutive trials.

Each 104 minute test session was completed under a different level of grasp force (i.e. 5, 15, and 25 % of an individual's grasp strength) and work:rest ratio (i.e. 15s grasp: 15 s rest, or 15s grasp: 7.5s rest). The six days

of testing required for an individual test subject was completed within a two to three-week period. See Figure 1 for a graphical summary of the experimental design employed.

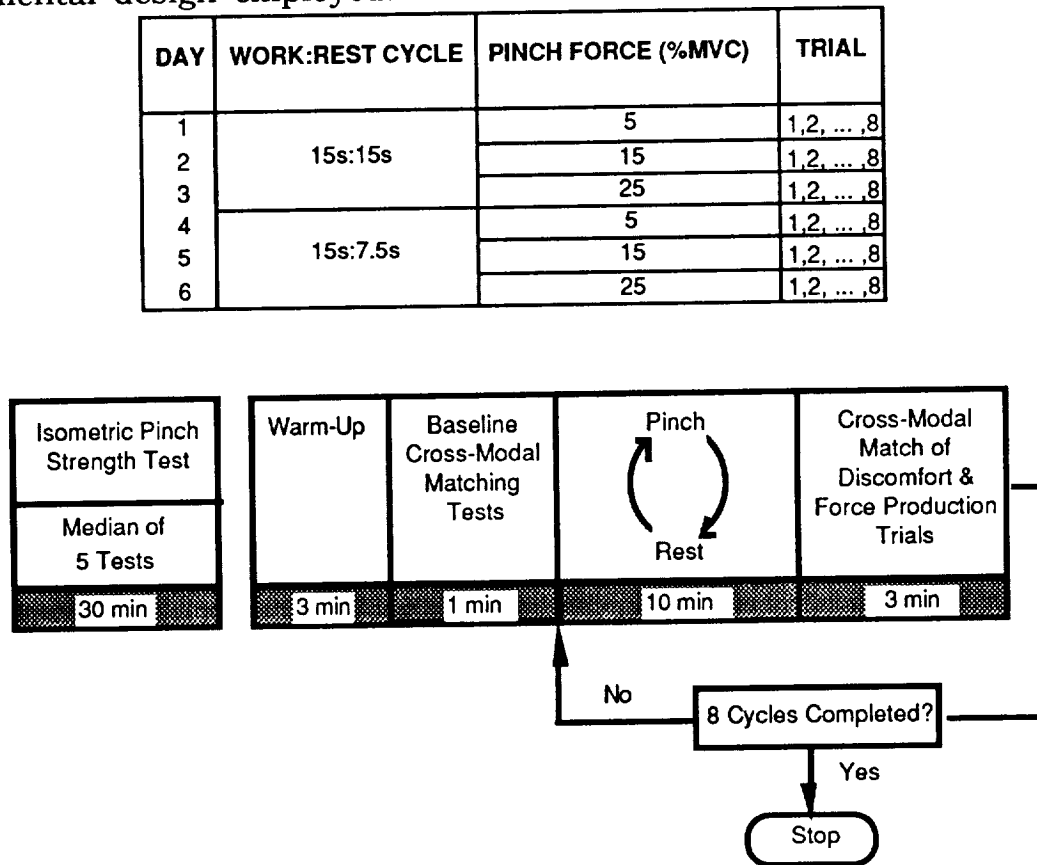


Figure 1. Experimental design and procedural paradigm.

Figure 2 describes the apparatus used to measure and to control pinch grasp forces. Subjects were seated in front of a computer display with the distal phalanx of the thumb and index finger seated against horizontal tabs mounted atop of two vertical metal struts. An adjustable platform was used to raise or lower the subject's hand to insure that all subjects could comfortably seat their fingers against the struts using the same hand posture. The struts, attached to an immovable base, possessed balanced strain gages which passed stress-induced voltages through an amplifier to an analog-to-digital converter, and subsequently to a microcomputer for recording and statistical analyses.

Two cursors, whose vertical positions on a computer display were independently controlled by normal forces applied to the struts, were presented on a computer screen and used to feedback grasp force magnitudes to the subject. Subjects were instructed to jointly move the cursors to, and to remain on, a visual target for a 15s period. Start and finish of the exertions were timed, and initiation and cessation of the grasps was visually and aurally signalled, by computer. Though distances of cursor movements to the target were fixed, forces required to acquire the target were set to 5, 15, or 25 percent of the individual's measured grasp strength capability. Real-time

recording of grasp force was monitored and used to confirm compliance with the experimental paradigm.

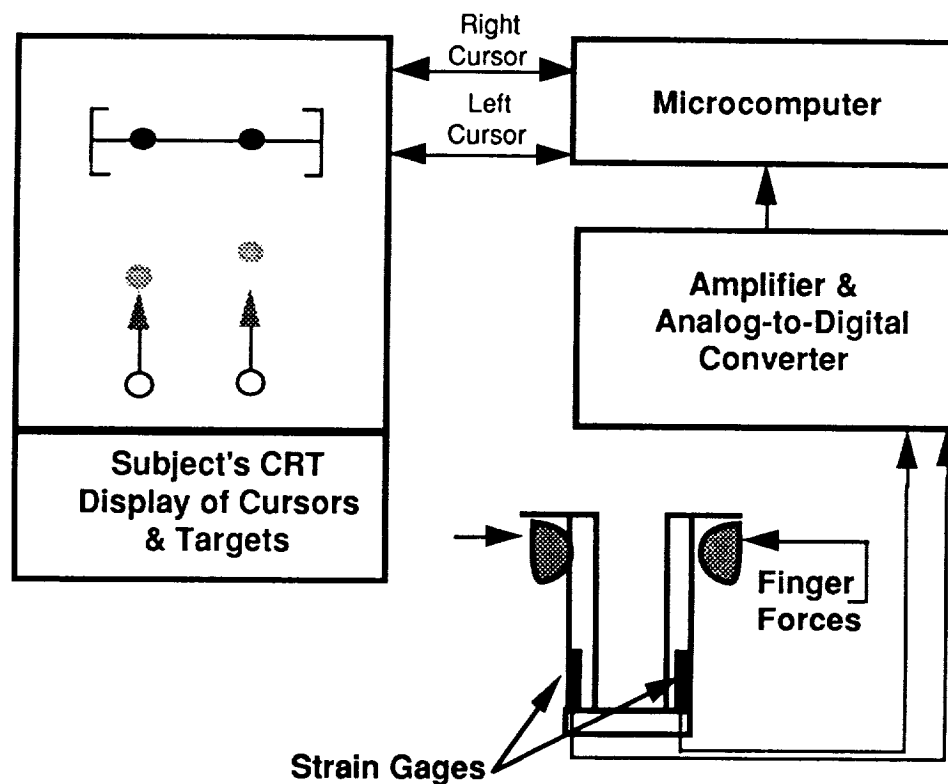


Figure 2. Experimental apparatus used.

Maximum pinch grasp strength, or maximum voluntary contractions (MVCs), were measured using the apparatus described in Figure 2. Subjects performed a series of 5 maximum effort grasps for a period of 5 s. Average normal forces produced by the thumb and index finger during the last three seconds of the exertion were used as estimates. The median of 5 exertions, separated by 3 minute intervals for recovery, served as the estimate of the subject's maximum grasp strength. The median value was used to set force magnitudes in experimental trials.

Subjects estimated the magnitude of fatigue and discomfort in the hand and forearm using a cross-modal matching method described in detail elsewhere [1]. Subjects adjusted the length of a visual analog scale, a line, which was anchored between no signs and symptoms, and maximum tolerable discomfort. Thus, if the individual judged that the severity of symptoms were equivalent to 50% of their tolerable range, then they adjusted the length of the line displayed on the computer screen to 50% of its maximum length.

A similar approach was used to gage the ability of a subject to judge grasp forces. Following the procedures outlined by Lodge [3], subjects were presented a series of visual lines of different length and were instructed to match by exerting a grasp force of equal intensity. Thus, presentation of a visual line equal to 50% of its possible length was to be matched by applying a

grasp force equal to 50% of the individual's perceived strength limit. Following a series of 5 trials, log-transforms of 2 s averages of stable force estimates (i.e. subjects reported when they believed that they had reached a stable exertion equivalent to the given line length) were plotted against log-transforms of line-lengths (i.e. 5, 20, 35, 50, and 65% of maximum line length), and a least-squares regression analysis was performed to estimate the slope of the plotted line. Forces produced during the 5 estimates were also recorded for subsequent analysis.

3. Results

Analysis of day-to-day baseline force magnitude estimation performance revealed no significant changes in average forces used to perform grasps, nor in the slopes of the force magnitude estimation test ($p > .10$) across test days. See Figure 3.

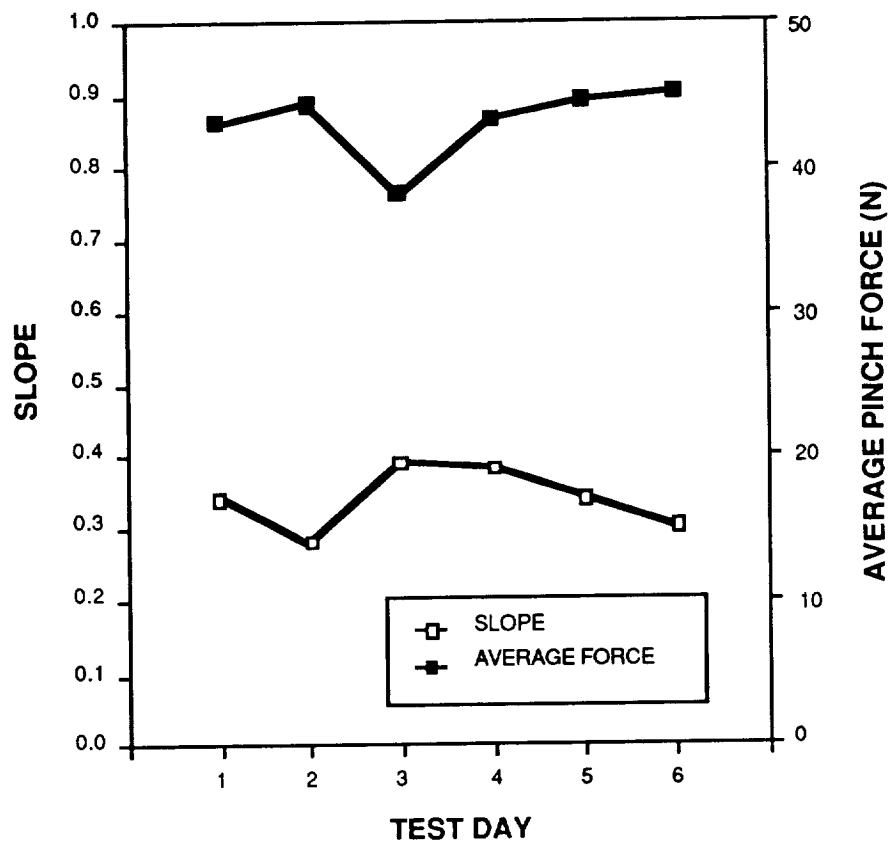


Figure 3. Force magnitude estimate slopes and average grasp forces produced during baseline tests.

Matching intensity of discomfort using a visual analog scale showed significant increases in discomfort occurred in response to increased pinch grasp force levels ($F=181.2$, $p < .05$), work:rest ratios ($F=13.4$, $p < .05$), and with progression of time ($F=25.1$, $p < .05$). Impact of work:rest ratio was significant only when subjects were exerting force levels of 25 percent of MVC ($F=12.6$,

$p < .05$). All remaining treatment interactions were not statistically significant ($p > .10$). See Figure 4.

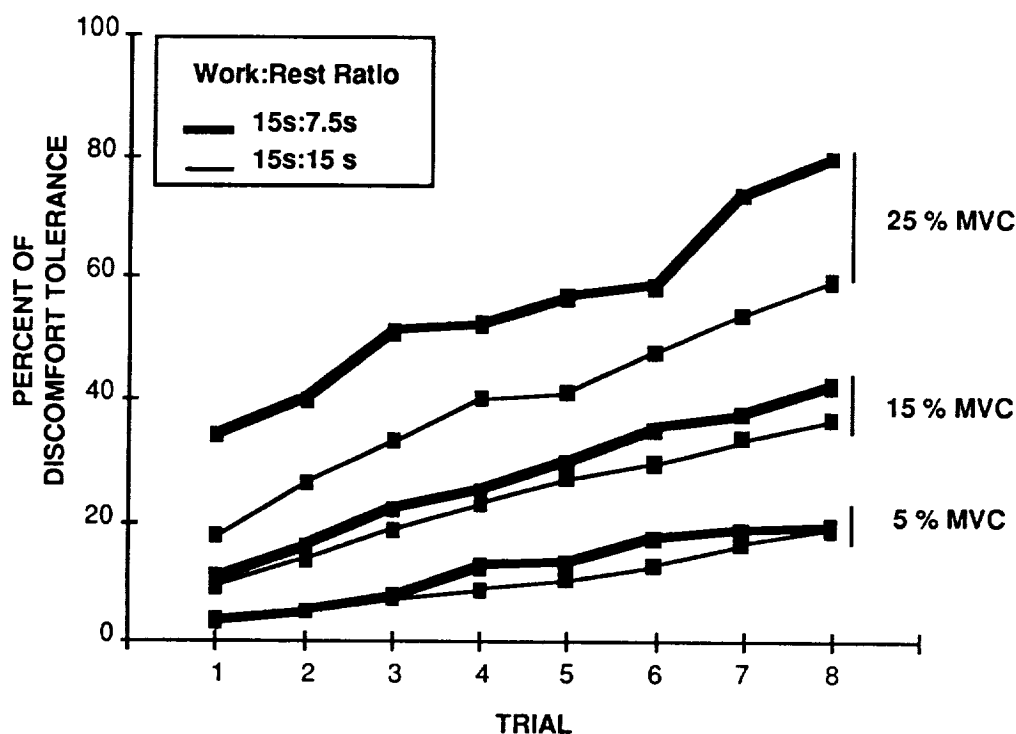


Figure 4. Percent of discomfort tolerance plotted as a function of pinch grasp force, work:rest ratio, and progression of test session.

Slopes of force magnitude estimation functions declined following test sessions in which pinch grasp forces exceeded 5 percent of MVC ($F=4.4$, $p < .05$), or when work:rest ratios were increased from 1 to 2 ($F=9.9$, $p < .05$). As shown in Figure 5, declines in slopes in response to increasing pinch force occurred only when work:rest ratios exceeded 1.0 ($F=3.4$, $p < .05$). All remaining main and interaction effects were neither materially or statistically significant ($p > .10$).

Unlike psychometric slopes, average pinch forces produced during magnitude estimation trials remained unchanged with only one exception ($p > .10$). Average pinch force increased slightly when work:rest ratios were increased from 1 to 2 ($F=7.4$, $p < .05$). See Figure 6.

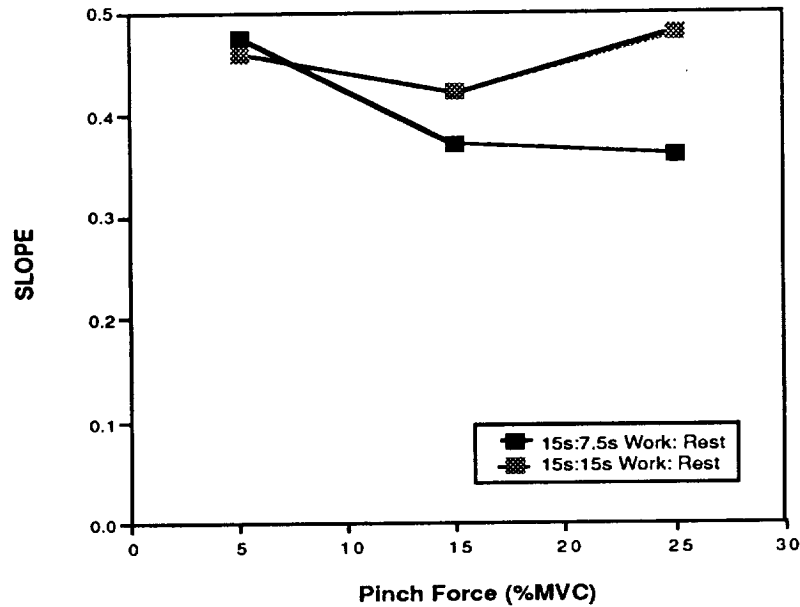


Figure 5. Slope of force magnitude estimation function plotted against pinch grasp force and work:rest ratio.

Correlation analyses showed direct relationships between magnitude of discomfort and magnitude of pinch force ($r = 0.80$, $p < .05$) and task duration ($r = 0.50$, $p < .05$). Slopes of force magnitude estimates declined when intensity of discomfort ($r = -0.40$, $p < .05$) and work:rest ratios ($r = -0.39$, $p < .05$) increased. Declines in slopes were also accompanied by increased average pinch force ($r = -0.48$, $p < .05$). All remaining correlations were not statistically significant ($p > .10$).

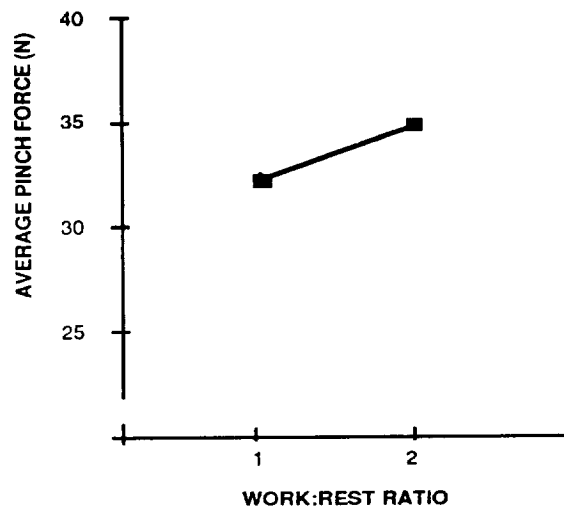


Figure 6. Average pinch grasp force during force estimation trials plotted across work:rest ratio.

4. Discussion and Conclusions

Subjects experienced some degree of fatigue or discomfort symptomatology even at relatively low levels of exertion (i.e. 5 % of MVC). At higher levels of grasp force (i.e. 25 % MVC) significant levels of discomfort were encountered in as little as 10 minutes. Discomfort, regardless of initial exertion level, continued to build with progression of the task in a constant manner. Work:rest ratios, or length of time provided to recover from the immediate consequences of the exertion, produced little or no effect until exertions exceeded 15 % of MVC. It is noteworthy that subjects rarely complained of discomfort or fatigue in musculature located in the forearm (i.e. the principal flexors of the digits). The thumb and index fingers, and tissues directly underlying finger contact on the smooth flat strut's surface, were the chief loci of discomfort. The direct mechanical stress could be tolerated at 15 % MVC with moderate reports of discomfort after 104 minutes. However, at 25 % of MVC a few subjects were near their tolerance limit, and would probably have been unable to complete a two-hour task. In earlier pilot experiments, some of our subjects were unable to complete the 104 minute protocol when grasp forces equalled 25 % of MVC.

Significant negative shifts in slopes of psychometric functions were found immediately when exertions equalled or exceeded 15 % of MVC and work:rest ratios were increased to 2.0. If subjects were provided sufficient rest between exertions (e.g. 15 s) then psychometric functions remained stable; regardless of exertion magnitude or level of persistent discomfort. There was no evidence to support the conclusion that shifts in psychometric functions were strictly a result of insidious loss of muscle contractility. Slopes pivoted about mid-range force estimates and were accompanied by significant elevations in slope intercept magnitudes. Subjects, thus, produced larger than expected forces when called upon to produce small exertions (i.e. 5 to 35 % of MVC), and smaller than expected exertions when forces equalled or exceeded 50 % of MVC. This finding, along elevations in force production occurring concomitantly with flattening slopes, suggests that subject's perceptions of exertions were probably perceptually-masked by ancillary sensations of discomfort. Maximum voluntary contractions are based upon both muscle contractile force capability and volitional tolerance of exertion-induced discomfort. Thus, reductions in force production, when significant levels of exertion were required, may reflect lost contractility of tasked musculature, a reduced volitional tolerance for additional exertion-induced discomfort, or both factors. It is interesting to note, however, that given sufficient time for masking effects, and perhaps loss of contractility, to decay, force magnitude estimation performance remained stable.

Telemanipulation is often characterized by repeated and sustained grasps of objects which are comparable to those studied in this experiment (e.g. object transport, part or tool transfer from one end-effector to another, or assembly or disassembly activities). Under such conditions operators of comparable master-controllers are likely to rapidly develop low to moderate levels of localized discomfort in the hand and fingers when forces of operation or reflected forces approach 15 % of MVC. If exertions reach 15 % of MVC,

and the operator is not provided substantial rest between exertions, then shifts in force perception can occur. Operators will over-force when exertion requirements are low, and underforce when grasp requirements are substantial.

Aside from the consequences of less delicate grasping, overforcing of grasps serves to further provoke, or to at least maintain, fatigue and discomfort symptomatology and its negative performance consequences. Negative shifts in psychometric functions found in this study can also result in inappropriate interpretations of the magnitudes of large forces reflected to the master-controller, and in underproduction of grasp forces required for more rigorous manipulation activities. Signs and symptoms of localized discomfort and fatigue always preceded untoward shifts in force perception. Unfortunately, the presence of discomfort or fatigue in the hand occurs rapidly and in the absence of psychometric shifts; thus, discomfort cannot be used as a reliable indicator of shifts in force perception.

5. References

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